Suitability of different approaches for analyzing and predicting the behavior of decomposed volcanic rocks

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ABSTRACT

Based on detailed investigation of decomposed volcanic soils from Hong Kong, an extensive analysis has been made into the best approaches for the prediction and description of the behavior of the decomposed volcanic rocks, materials which are commonly encountered by practicing engineers worldwide. The parameters considered were compressibility, strength and in-situ specific volume, and the indices considered were plasticity, a grading descriptor (fines content), mineralogy (clay minerals and quartz) and chemical weathering indices. The sampling depth and chemical weathering indices are the most appropriate factors to predict the compressibility of the decomposed volcanic rocks. The strength will be satisfactorily predicted by fines content, clay minerals, plasticity and chemical weathering indices while the depth, plasticity and chemical weathering indices are most appropriate for predicting the in-situ specific volume. The various approaches (depth, fines, mineralogy, plasticity and chemical weathering indices) are each suitable for different parameters and are therefore recommended for the practising engineers working on these geomaterials, depending on which properties are needed.

Keywords: Compressibility, Strength, Specific volume, Mineralogy, Plasticity, Chemical indices

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INTRODUCTION

Decomposed rocks are abundant in tropical and subtropical areas of the world, so these geomaterials are encountered by practicing engineers worldwide and engineering works commonly carried out in or on them. In Hong Kong particularly, a substantial part of the territory is occupied by granitic and volcanic rocks. These rocks have been subjected to physical disintegration and chemical decomposition, termed weathering, over a long period of time, promoted by the subtropical nature of the climate. The majority of the geotechnical problems in Hong Kong are therefore related to decomposed igneous rocks and many of them occur in the decomposed volcanics. However, there are difficulties in analyzing the mechanical behavior of these geomaterials for geotechnical design compared to sedimentary soils which have been more extensively studied. The effects of weathering in saprolites obtained from igneous rocks of tropical and subtropical regions have been studied by many researchers (e.g. Futai et al., 2004; Ng and Chiu, 2001) and recently, attempts have been made to describe the behavior of decomposed saprolites using a critical state based approach that includes the effects of structure (e.g. Okewale and Coop, 2017; Rocchi and Coop, 2015) similar to those that have been used in sedimentary soils (e.g. Burland, 1990; Cotecchia and Chandler, 2000).

Okewale and Coop (2017) studied the effects of weathering on soils derived from decomposed volcanic rocks. They found that the properties changed in a manner that was consistent with the increasing of fines content and plasticity as a result of weathering. Similarly, for granitic saprolites Rocchi and Coop (2015) found a clear change to the mineralogy that accompanied a grading that became finer and better graded as the weathering increases or depth reduces. Some of the studies on weathered geomaterials have examined the vertical and/or lateral variability and the properties were often defined based on the profiles (depth) and/or various indices (e.g. grading descriptors, mineralogy). However, few have tried to identify which are the best predictors of geotechnical behavior in these materials.

In this paper, attempts are made to provide suitable approaches for predicting the strength and compressibility parameters that might be needed for geotechnical analysis; no similar study has been carried out for decomposed volcanic rocks. Apart from trying to relate engineering parameters to depth, which is a typical geotechnical engineering approach that typically works well in sedimentary soils, they might instead be related to chemical or physical indices used to capture the degree of weathering, such as grading descriptors (e.g. fines content), mineralogy (e.g. clay minerals, quartz content), plasticity or more complex chemical weathering indices. The sampling depth is not an index per se but it is very important from the geological point of view, as the weathering degree broadly progresses with depth, and also from the practical point of view for the engineer. The slope of the critical state line (M), which is directly related to the critical state angle of shearing resistance, is chosen for the strength parameter, since most samples did not have significant peak strengths at their in-situ stress levels, while the slope of the isotropic and one-dimensional normal compression lines (λ) and the intercept of the one-dimensional normal compression line (N_o) are used as the compressibility parameters. Also, the in-situ specific volume is used as a parameter to represent the in-situ state because of its importance in describing and predicting the behavior of the soils in conjunction with stress.

The purpose of these correlations is not as an alternative to good quality laboratory and/or field testing, but only to act as a guide for engineers to identify likely values at an early design stage, to be able to interpolate between the data that they have for other locations and for them to identify easily data that are unreliable and tests that need repeating. These correlations are specific to the Hong Kong decomposed volcanic rocks, but it is anticipated that similar correlations, although probably with different numerical values, will apply to other weathered volcanic soils and that the general approach is likely to be more widely applicable. The data presented in this paper are for three different formations, including two described by Okewale and Coop (2017). For the additional formation, apart from several classification and index tests, scanning electron microscope (SEM), X-ray diffractometer (XRD) and X-ray fluorescence spectrometer (XRF), the mechanical behavior was studied by conducting oedometer and triaxial tests on the intact and reconstituted samples.

MATERIALS TESTED

The samples tested were decomposed volcanic rocks of various degree of weathering ranging from Highly Decomposed Volcanic rocks (HDV, Grade (IV)) to Completely Decomposed Volcanic rocks (CDV, Grade (V)). The samples were taken as blocks and Mazier rotary cores from different locations, depths and three formations, the Ap Lei Chau (ALCF), Mount Davis (MtDF) and Tai Mo Shan (TMSF). While details of the samples from the ALCF and MtDF have been given by Okewale and Coop (2017), the details of the samples from the TMSF are given in Table 1. The samples were classified according to visual inspection at the time of sampling by engineers or geologists on site based on GEO (1988), Irfan (1996) and ISRM (2007). The TMSF are coarse grained materials and the Mazier samples were from two different locations belonging to extremely weak completely decomposed volcanic rocks (ewCDV). The samples were taken from 4-5m and 10.7-11.7m depths. A map of the sampling locations is shown in figure 1. While Okewale and Coop (2017) investigated the evolution of the physical properties, mechanical behavior and geological structure of decomposed volcanic rocks with varying degrees of weathering, this study investigates suitable approaches for predicting different parameters required for geotechnical problems.

METHODOLOGY

The fines content was estimated from the particle size distribution curves as shown in figure 2, determined using wet sieving and sedimentation techniques. The curves are for the samples of different weathering degrees, from different locations and the three different formations. The samples may be classified as Highly Decomposed Volcanic (HDV) and Completely Decomposed Volcanic rocks (CDV). These classifications are further sub-divided as shown in figure 2. Broken lines indicate the CDV and solid lines the HDV, an increase in line weight and darker colors corresponding to a decrease in the degree of weathering. The broken lines with symbols are for the TMSF. The demarcation at 0.063mm is used to divide the grading into fines and sand contents, according to the British Standard. The plasticity index (Ip) was chosen as one of the physical index properties to be investigated, for which the liquid limit (LL) and plastic limit (PL) were determined through Atterberg limit tests (BS 1377:2:1990).

An accurate calculation of specific volume is very important because the in-situ behavior will be directly related to this, combined with the stress level. The in-situ specific volumes ($v = 1+e$) were calculated by careful measurements using several different methods in order to improve confidence, following the methods outlined in Shipton and Coop (2012) and Rocchi and Coop (2014). The initial v of each recovered sample was obtained from the sample weight, initial dimensions and water content, while final measurements were also used as verification, back-calculating the initial v using the volumetric strains measured in the test. The equations used were chosen to be as independent to each other as possible:

$$v_i = \frac{\Upsilon_w(1 + w_i)G_s}{\Upsilon_{bi}} \qquad (1)$$

$$v_i = \frac{\Upsilon_w(1 + w_f)G_s}{\Upsilon_{bf}(1 - \varepsilon_{vol})} \qquad (2)$$

$$v_i = \frac{w_f G_s + 1}{(1 - \varepsilon_{vol})} \qquad (3)$$

where v_i is the initial specific volume, G_s specific gravity, w_i initial water content, w_f final water content, Υ_w the unit weight of water, Υ_{bi} initial bulk unit weight, Υ_{bf} final bulk unit weight and ε_{vol} is the volumetric strain.

The quantitative bulk mineralogy was determined using a Bruker X-ray diffractometer, analyzing the sample in a powder form. The minerals were identified in the range of $5^0 \leq \theta \leq 50^0$ and $10^0 \leq 2\theta \leq 100^0$ with Cu-Kα radiation at 30kV and 10mA and the samples were scanned at an interval of 0.02^0/0.8 s. Clay minerals, feldspars and quartz were quantified but the feldspars were not used as an index because the clay minerals result generally from the alteration of the feldspars.

The chemical weathering descriptors, referred to here as indices, and sometimes called alteration indices, are commonly used for characterizing weathering profiles, usually plotting them against the depth or the corresponding degree of weathering, thereby providing a visual trend of the changes in the major bulk elemental oxides with the degree of weathering. Seventeen indices were evaluated, the details of which and the formulae used are presented in Table 2. These have been used for profiles developed in igneous rocks (e.g. Ng et al., 2001; Sutton and Maynard, 1992; Duzgoren-Aydin et al., 2002; Irfan, 1996, 1999) and metamorphic rocks (e.g. de Jayawardena and Izawa, 1994; Gardner and Walsh, 1996; Price and Velbel, 2003). The degree of decomposition (Lumb, 1962), is defined as Xd = (Nq-Nqo)/(1-Nqo), where Nq and Nqo are the weight ratio of quartz to quartz and feldspar in the sample and the original rock respectively. This has been used extensively (e.g. Collins, 1985; Baynes and Dearman, 1978) but was not used here because the data for the original parent rocks were not available as only grade IV and V materials were sampled; this would be typical of many site investigations. For the same reason, the lixiviation index defined as β = $((K_2O+Na_2O)/Al_2O_3)_{weathered}/(((K_2O+Na_2O)/Al_2O_3)_{fresh}$ (Rocha-Filho et al., 1995) was not used. Also, the common and simple method of separating the grains by hand under a microscope was not feasible for these volcanic materials. Even if some of these indices were developed for different types of rock, they were tried to see whether they would be effective. The qualitative and quantitative bulk chemical analyses of the samples of different weathering degrees were carried out using a Shimadzu EDX-720 energy dispersive X-ray fluorescence spectrometer (XRF) and the samples were again analyzed in powder form. The chemical weathering indices were calculated in the molecular proportions of the major elemental oxides.

The slope of the normal compression line when a natural logarithmic stress scale is used (λ) and the intercept taken here at a vertical stress of 1kPa (N_o) were obtained from oedometer test data as discussed by Okewale and Coop (2017). Within the range of the stress tested, the normal compression lines are straight lines. The slope of the normal compression line (NCL) is taken as $\lambda=C_c/2.303$, where C_c is the compression index defined in terms of vertical effective stress. The data for these highly heterogeneous soils tended to be rather scattered so it was assumed that the gradients of the one-dimensional normal compression line, isotropic normal compression line and the critical state line defined by the end of shearing states, were all parallel in the v:lnp' plane, where v is the specific volume and p’ is the mean normal effective stress for the triaxial tests. The intercept of the normal compression line (N_o) was taken here as the specific volume at a vertical stress of 1kPa.

Instead of using compression parameters at large strain levels, it might have been desirable to try to use a parameter more directly related to the structure of the soil, such as the yield stress in compression. The difficulty with this is that it is influenced by 1) the effects of structure, 2) the location of the intrinsic normal compression line and 3) the in-situ specific volume. The combined effects make the change of yield stress with weathering degree unclear (Okewale and Coop, 2017). The ratio between metastable and granular compressibility defined by Vaughan et al. (1988) and Viana da Fonseca (1998) was also not used because it too depends on the location of intrinsic normal compression line and the yield stress.

The strength parameter M, which is the critical state line gradient in q:p' axes, was obtained from the triaxial test data and the details of the testing methodology have been discussed in Okewale and Coop (2017). The parameter M is used because it is one of the basic properties in the critical state framework, and also because for most samples there was no pronounced peak strength. The gradient M is related to the critical state angle of shearing resistance (φ'_{cs}) for compression by $\sin\varphi'=3M/(6+M)$).

RESULTS AND DISCUSSIONS

A Depth-based approach

Due to the significance of depth for both the geology and practical application, both the parameters and the indices have been analyzed in terms of depth (figure 3), hoping also to highlight the trend with degree of weathering, which should generally increase with depth. In all the plots in this paper, open symbols are used for the CDV with a reduction in size corresponding to reduced weathering and filled symbols are used for the HDV. The large grey cross symbols are used for the ewCDV of the TMSF. The trends identified on figures 3 are represented by either straight regression or estimated curved trend lines, if necessary. The compressibility parameters λ and N_o (figure 3, a & b) both reduce significantly with depth and have also been found to increase with the degree of weathering (Okewale and Coop, 2017).

A good correlation is indicated by a high correlation coefficient (r), which is the quantitative strength of the relationship between the parameters and indices and low *p* value, an indication of the probability of a true relationship between the parameters and indices. Due to the heterogeneous nature of the samples, a critical *p* value greater than 0.06 is assumed to be statistically insignificant. The slope λ shows a moderate linear relationship with depth, having an r of 0.58 and *p* of 0.049. The intercept N_o shows a stronger correlation, with r and *p* of 0.61 and 0.026 respectively, and so is more reliably related to depth than the slope may be. Generally, a depth-based approach performs quite well for predicting the compressibility, compared to other methods. Within the scatter of the data, M increases slightly (figure 3(c)), but the relationship is weak, with $r = 0.36$ and $p = 0.203$. This indicates that a depth-based approach is not suitable for the analysis and prediction of strength. In figure 3(d), apart from the scatter resulting from the heterogeneity of the samples, the in-situ v reduces with depth, with good statistical significance ($r = 0.72$ and $p = 0.0001$). The in-situ state may therefore be related to depth reasonably satisfactorily. The plasticity index (Ip) and fines (figure 3(e and f)) also reduce with depth. The regression statistics are significant with $r = 0.58$ and $p = 0.011$ for Ip and $r = 0.68$ and $p = 0.007$ for fines, and so an analysis in terms of depth may also be suitable for the grading and the resulting plasticity. Comparing the values of the fines content and plasticity with granitic saprolites studied by Begonha and Sequeira Braga (2002), the values are much higher and the variation in the values result from heterogeneity and the variation of parent rocks.

Figure 4 presents the variation of some chemical weathering indices with depth and the trends are represented by linear regression lines. The details of the other indices that are not shown are given in Table 3 with their regression statistics. In some of these, although not shown, linear regression lines did not work very well and estimated curved trend lines were used instead. This was generally caused by the scatter in the data at shallow depths, particularly arising from some shallow HDV samples. The chemical weathering indices yield a range of regression statistics ranging from very weak to very strong correlations.

The Weathering Potential Index (WPI) increases with depth and it can be said that it broadly reduces with weathering as shown in figure 4(a), although the weathering does not proceed linearly with depth and is typically heterogeneous in nature. The WPI measures the removal of the cations from the rocks during weathering processes and as the weathering progresses, more cations are removed and this will lead to a reduction in the value of WPI and vice versa. The relationship between WPI and depth is statistically significant with an r of 0.88 and *p* value of 0.003. The WPI has also been found to be a good indicator for the weathering degree of decomposed granitic rocks (e.g. Irfan, 1996, 1999; Ng et al., 2001). The Weathering Index of Parker (WIP) shows a similar trend to WPI with a very strong linear relationship with depth with $r = 0.81$ and $p = 0.001$. The WIP is based on the amount of cations present in the rock as well as considering the mobilities of some elements (sodium, potassium, magnesium and calcium). An increase in the intensity of weathering reduces the presence of cations, and so reduces the WIP. The WIP has been found to be appropriate for characterizing the weathering profiles of metamorphic rocks (e.g. Price and Velbel, 2003).

The Loss on Ignition LOI gives an indication of the water contents in the samples, and this reduces with depth (figure 4c) with an r of 0.89 and p of 0.002, again indicating a strong relationship. The increase in weathering leads to an alteration of minerals in rocks to clays with a greater potential for water retention, causing a higher value of LOI. Ng et al. (2001) also found LOI to be good indicators for weathering degree in decomposed granitic rocks.

Figures 4(d, e & f) present the variation of Chemical Index of Alteration (CIA), Plagioclase Index of Alteration (PIA) and Chemical Index of Weathering (CIW, also called Alumina to Calcium-Sodium Ratio, ACN) with depth. These all reduce with depth. The CIA measures the conversion of feldspars to clays and CIW is almost the same as the CIA except that potassium oxide is eliminated from the formula. The PIA is an alternative to the CIW. At shallow depths, where the intensity of the weathering is generally highest, the feldspars have been substantially converted to clays which results in higher values of the indices. Very strong correlations exist between CIA and PIA, and depth, with similar correlation coefficients (0.80 & 0.79) and the same *p* value (0.002). The CIW also has a strong linear relationship with depth with a correlation coefficient of 0.68 and *p* value of 0.015.

The strongest linear relationships with depth are found for the WPI, WIP, CIA and LOI, so this may be an indication that these may be best chemical indices suited for characterizing weathering profiles in decomposed volcanic rocks, although how they are related to engineering properties is discussed below. The PIA, CIW/ACN, Hydration Coefficient (Hc, which relates water content with mobile elemental oxides), Leaching Coefficient (Lc, which relates silica with mobile elemental oxides), Alumina to Potassium-Sodium Ratio (AKN) and Vogt's Residual Index (VRI) also have statistically significant correlations and strong linear relationships with depth (see Table 3). Moderate correlations are found for Sesquioxides Content (SOC, a combination of oxides of iron and aluminum) and Residual content (Rc, relating SOC to mobile elemental oxides). The Weathering Product Index (PI, quantifying non-mobile elemental oxides), the Silica to Alumina or Ruxton Ratio (SA/R) and the Silica-Titania Index (STI) all have weak correlations and are insignificant statistically. The Silica-Sesquioxides Ratio (Kr) has an especially weak correlation. The chemical weathering indices that combine several chemical oxides, particularly the alkali and alkali earth elements, as well as those that have a water content in their formulation, therefore seem to be those that are most suitable for characterizing weathering profiles in decomposed volcanic rocks.

In practice, since a depth-based approach in which vertical are plotted may be suitable for some engineering parameters and also depth is well related to some indices, this approach will often help the practicing engineer determine reliable engineering parameters within often large spatial variations. While good quality testing is always needed, it might reduce the number of tests and help to identify which data are unreliable. Similarly, an understanding of spatial variability allows the most critical areas and depths for a design to be targeted.

An indices-based approach

An index is any descriptor of a material, and here those that might be related to parameters that quantify engineering behavior (e.g. strength or compressibility) are those of interest. In addition to the more complex chemical indices discussed above, other indices that might be used are those based on physical properties or the mineralogy, the ones used here being fines content and plasticity index, which will be referred to as "physical indices" and clay mineral or quartz content, which are mineralogical indices. On each of the plots presented relating indices to engineering parameters, the trends are represented by regression lines and in each figure examples are given for the best and worst regression statistics, details of which are given in Table 4.

Figure 5 presents the variation of the compression line slope λ with some of the indices. The most weathered samples have higher SOC values and λ increases with SOC (figure 5(a)), with a very strong linear relationship (r = 0.85, p = 0.001). The most weathered samples also have lower values of weathering product index (PI) and λ reduces with PI with again a very strong correlation coefficient of 0.84 and p of 0.001 (figure 5(b)). The relationship between slope and Hc is shown in figure 5(c). The correlation is similar to that of SOC with an r of 0.82 and p value of 0.011. However, as for all the Hc correlations given in this paper, while the correlation factors may appear good, the data are marred by there only being one large Hc value, and so the conclusions regarding Hc must be tentative. The compression line gradient also reduces with STI and there is a strong linear relationship between them which is statistically significant (r = 0.81, p = 0.002) (figure 5(d)). The WIP, WPI, LOI, Rc, Kr, AKN, VRI, SA/R, CIA and PIA all have strong linear relationships with λ (Table 4), but the Lc and CIW/ACN have only moderate correlations that are statistically insignificant. The chemical weathering indices are therefore mostly good predictors of the compression line gradient.

In contrast, the correlations with physical and mineralogical indices are less convincing. In figure 5(e), λ seems to reduce with quartz content but this shows the poorest correlation (r = 0.07, p value = 0.96), even if the most weathered sample has the lowest quartz content. This is, however, expected because, apart from the most weathered samples at the shallowest depths, the quartz contents do not really vary much with depth and weathering degree. Similarly, in figure 5(f), λ seems to be increasing with clay mineral content and the most weathered samples have the highest clay minerals, but the correlation is again very poor (r = 0.17, p value = 0.66). This is an indication that a simple mineralogy based index is a poor predictor of the compressibility. The value of λ increases with fines content, but again not with reasonable statistical significance (r = 0.44, p = 0.118). It also increases with plasticity index (Ip) but the correlation is again weak (r = 0.50, p = 0.094), as shown in Table 4. Fines content and Ip cannot therefore be used as satisfactory indicators of the compressibility of decomposed volcanic rocks.

The variation of the intercept N_o with some of the indices is given in figure 6. Figures 6 (a, b & c) present the variations of the N_o with Hc, SOC and PI respectively and these show direct similarities with their relationships for λ, although the regression statistics are slightly different, but are again statistically significant. Figure 6(d) shows that N_o reduces with WPI, with a very strong linear relationship (r = 0.82 and p = 0.021). The other chemical weathering indices that are not shown also have direct similarities with the relationships for slope (Table 4) except for STI which falls marginally into the strong correlation category. The chemical weathering indices are therefore generally good indicators of the intercept, which is the other key parameter quantifying compressibility.

Figures 6 (e & f) present the variations of the intercept with quartz and clay mineral contents. Again, these show similarities with λ having the poorest correlations, although the most weathered samples have lower quartz and higher clay mineral contents. Mineralogy will therefore also be a poor predictor of the intercept. The variations of the intercept with fines and Ip also show similarities to those for λ, with insignificant statistical correlations, as shown in Table 4. Again, simple physical indices like fines and Ip are poor predictors. Table 5 shows the equations correlating some indices and the compressibility parameters. Only few are shown, focusing on those that are very significant statistically. These could be used to estimate the compressibility of decomposed volcanic rocks in Hong Kong and might form the basis for wider application if they could be verified with data for saprolites of weathered volcanic rocks from elsewhere. Generally, a chemical weathering indices based approach is suitable for compressibility while simpler indices are not satisfactory.

In figure 7, the variation of the strength parameter M with some indices is presented. The value of M reduces with Hc and SOC with a strong linear relationship (r = 0.82 & 0.74, p = 0.012 & 0.037) (figure 7(a & d)). The value of M reduces with fines content, as might have been expected, with a strong linear relationship (r = 0.78, p = 0.003) (figure 7(b)), and fines content is therefore a good predictor of M. It also reduces with plasticity index (Ip) with a strong correlation coefficient of 0.76 and p value of 0.003 (figure 7(c)), which again indicates Ip is satisfactorily related to M. Both of the physical indices give good correlations for strength, in contrast to compressibility.

The relationships between M and CIW/ACN, VRI, WIP, CIA or PIA show very poor correlations and they cannot be used for predicting M. The relationship between M and quartz content also shows insignificant statistics (r = 0.30, p = 0.42), which is expected because of the lack of change of quartz content with weathering highlighted above. However, there is a statistically significant relationship between M and clay mineral content, with a strong correlation coefficient of 0.67 and p value of 0.042. Clay mineral content is therefore a good indicator of M while quartz content is a poor predictor. The WPI, PI, LOI, Rc, Kr, AKN, SA/R and STI also all have strong linear relationships with M, with regression statistics as shown in Table 4. Table 6 presents the equations relating some of the indices and M, again only giving those with statistically significant correlations. In general, with the exception of quartz content, the physical and mineralogical indices fared better for strength than they did for compressibility and the performance of the chemical indices was more patchy.

The variations of in-situ specific volume (v) with WIP and WPI are shown in figure 8(a & b). It reduces with both and the linear relationships have very good correlation coefficients and p values (r = 0.90 & 0.90, p = 0.0001 & 0.003). The in-situ v also increases with CIA and LOI with very strong correlations (r = 0.88 for both, p = 0.0002 & 0.003) as shown in figure 8(c & d). The in-situ specific volume also has very strong correlations with Hc, Lc and PIA (Table 4), while PI, SOC, Rc, AKN and STI all have strong linear relationships. The correlations for VRI, CIW/ACN and SA/R have moderate statistical significance while Kr has the poorest regression statistics (r = 0.46, p = 0.132) and therefore cannot be used to characterize the in-situ v.

Figure 8(e) presents the variation of the in-situ v with clay mineral content. This gives a poor correlation with a coefficient of 0.31 and p value of 0.379. A poor correlation is also found for the quartz content which indicates that mineralogy alone cannot be used to predict the in-situ v. The regression statistics of the relationship between the in-situ v and fines are marginally not significant (r = 0.52, p = 0.067), but it does give a good relationship with plasticity index Ip (Table 4) with a correlation coefficient of 0.60 and p value of 0.041. The equations relating some of the indices and the in-situ specific volume are given in Table 7. Only a selection of the more statistically significant ones is presented. In summary, for the in-situ specific volume, the chemical indices are generally the most successful, while mineralogy and fines content perform poorly. Of the simpler physical indices, only plasticity index was useful.

Geotechnical engineers tend only to use the physical indices and so the cross-correlations of these with the chemical indices and between each other may be of interest. Figure 9 shows the variation of Ip and fines content with some of them. The value of Ip seems to increase with Hc and fines content with strong correlations (figure 9(a & b)), although the data for Hc are rather bunched. The cross-correlations between Ip and the various indices are generally good except for the Lc, Rc and PIA (Table 4). Also, the fines content reduces with WPI and increases with the LOI with strong correlations (figure 9(c & d)) and generally most of the cross-correlations between fines content and various indices are again good, except for the Kr, STI and VRI. Some of the equations for the cross-correlations between the indices are presented in Table 8. Generally, the cross-correlations between various indices are good and useful, but it is interesting that those between the physical indices, fines content and Ip and the mineralogical ones, quartz and clay content, are generally not better than those for the chemical indices.

The performance of the indices has so far been assessed against the engineering parameters (compressibility, strength and in-situ-v) separately, but since engineers may be limited in the number of indices they can request, it would be interesting to evaluate which is best overall for all the parameters combined. This was done by assigning a tentative numerical value to the correlation coefficients based on the classification suggested by Evans (1996), shown in Table 9. The values for each index are added together for the different parameters and the values converted to percentages (Table 10). A new performance classification is then made as follows: (i) 0-25% is classified as very weak, (ii) 25-50% weak, (iii) 50-75% good and (iv) 75-100% “the best”. Based on this the Hc has the highest score because it has very strong correlations with all the parameters, although, as mentioned above, the correlation may be artificially good because of the scarcity of high Hc values. This is followed by WPI, PI, SOC, LOI, STI, Rc and AKN with performance values in that order, which are all classified as “the best”. The WIP, Kr, SA/R, CIA, PIA, Ip, fines, depth, VRI and Lc all have overall “good” performance. The CIW/ACN and clay mineral content performances are weak because they have poor correlations with some individual parameters. Quartz content has overall a very weak performance because it does not really show good correlations with many parameters. This underlines that a traditional approach of plotting data against depth, or trying to correlate engineering parameters with simple physical indices such as fines content or Ip may not be the most productive approaches, and that many of the various chemical indices are more successful. Quantifying the mineralogy is surprisingly not useful.

CONCLUSIONS

A detailed study of the best approaches to predict and describe the behavior of decomposed volcanic rocks with various degrees of weathering, from different locations and covering three different formations has been conducted. Apart from the scattered data due to heterogeneous nature of the samples, the compressibility and strength parameters, in-situ v, plasticity index, fines content and all the chemical weathering indices give expected and appropriate trends (either increasing or decreasing) with depth, with a range of regression statistics. It is interesting to see that for the decomposed volcanic rocks studied, the chemical weathering indices are especially useful to characterize the profiles, as was found in studies for other rocks. Some of the indices discussed may therefore be useful to the engineer in interpolating between test data, but they should not be seen as an alternative to laboratory or field tests. The equations provided can be used as a guide to estimate engineering parameters required for geotechnical design, especially in the preliminary design stages, where data may be limited. The relationships derived also help understand how the geotechnical parameters are related to the geological decomposition processes.

A traditional approach of plotting data against depth works well for compressibility, but otherwise the chemical indices are the best approaches for compressibility. For strength, the fines and clay mineral contents, plasticity and most of the chemical indices are all good approaches, while the depth, plasticity and most of the chemical indices-based approaches are the most suitable for the in-situ specific volume. It is interesting to see that the cross-correlations between many of the indices are generally very good. Overall, most of the chemical indices-based approaches are suitable for all the engineering parameters and therefore are the best. The fines and depth-based approaches are also often good, while the mineralogy-based approaches are much less successful. This emphasizes that a practicing engineer may plot engineering parameters against depth, in the traditional style, and this may be of some use, but that this should only be done in conjunction with information from one or more of the chemical indices if the best soil characterisation is to be made.

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Notation

C_c compression index

C_m clay minerals

F fines content

LL liquid limit

M critical state gradient *(q/p')*

N_o 1D-NCL* intercept at 1kPa

Ip plasticity index

PL plastic limit

p' mean effective stress

q deviatoric stress

v in-situ specific volume

λ slope of 1D-NCL* taken as $C_c/2.303$

φ'_{cs} critical state angle of shearing resistance

σ'_v vertical effective stress

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Table 1. Details of the samples from the TMSF

Location	Sample type/Borehole	Formation	Weathering degree	Depth (m)	Grading
L	Mazier (DH1)	Tai Mo Shan	ewCDV	4-5	Coarse
M	Mazier (DH2)	Tai Mo Shan	ewCDV	10.7-11.7	Coarse

TMSF Tai Mo Shan Formation, ew extremely weak, CDV Completely Decomposed Volcanic rocks

Table 2. Details of the chemical weathering indices evaluated

Index	Formula	Reference
Weathering Potential Index (WPI)	$100*[(K_2O+Na_2O+CaO+MgO-H_2O^+)/(SiO_2+Al_2O_3+Fe_2O_3+TiO_2+K_2O+Na_2O+CaO+MgO)]$	Reiche, 1943
Weathering Product Index (PI)	$100*[SiO_2/(SiO_2+TiO_2+Fe_2O_3+Al_2O_3)]$	Reiche, 1943
Weathering Index of Parker (WIP)	$[(2Na_2O/0.35)+(MgO/0.9)+(2K_2O/0.25)+(CaO/0.7)]$	Parker, 1970
Silica-to-Alumina Ratio or Ruxton (SA, R)	SiO_2/Al_2O_3	Ruxton, 1968
Chemical Index of Alteration (CIA)	$100*[Al_2O_3/(Al_2O_3+CaO+Na_2O+K_2O)]$	Nesbit & Young, 1982
Chemical Index of Weathering (CIW)	$100*[Al_2O_3/(Al_2O_3+CaO+Na_2O)]$	Harnois, 1988
Plagioclase Index of Alteration (PIA)	$100*[(Al_2O_3-K_2O)/(Al_2O_3+CaO+Na_2O-K_2O)]$	Fedo et al., 1995
Silica-Titania Index (STI)	$100*[(SiO_2/TiO_2)/((SiO_2/TiO_2)+(SiO_2/Al_2O_3)+(Al_2O_3/TiO_2))]$	de Jayawardena & Izawa, 1994
Vogt's Residual Index (VRI)	$(Al_2O_3+ K_2O)/(MgO+ CaO+ Na_2O)$	Vogt, 1927
Sesquioxide Content (SOC)	$Al_2O_3+ Fe_2O_3$	Irfan, 1996
Leaching Coefficient (Lc)	$SiO_2/(K_2O + Na_2O + CaO + MgO)$	Li et al., 1995
Residual Coefficient (Rc)	$(Al_2O_3+ Fe_2O_3)/ (K_2O + Na_2O + CaO + MgO)$	Li et al., 1995
Hydration Coefficient (Hc)	$H_2O^+/(K_2O + Na_2O + CaO + MgO)$	Li et al., 1995
Silica-Sesquioxide Ratio (Kr)	$SiO_2/(Al_2O_3+ Fe_2O_3)$	Moignien, 1966
Alumina to Calcium-Sodium Ratio (ACN)	$Al_2O_3/(Al_2O_3+CaO+Na_2O)$	Harnois & Moore, 1988
Alumina to Calcium-Potassium Ratio (AKN)	$Al_2O_3/(K_2O +Na_2O)$	Harnois & Moore, 1988
Loss on Ignition (LOI)	H_2O^+ content of samples heated to over 1000^0C	Suoeka et al., 1985

Table 3. Details of regression statistics of the chemical weathering indices with depth

Chemical weathering indices	Regression statistics	
	r	*p*-value
WIP	0.81	0.001
WPI	0.88	0.003
PI	0.35	0.260
SOC	0.40	0.180
LOI	0.89	0.002
Hc	0.72	0.040
Lc	0.77	0.003
Rc	0.54	0.060
Kr	0.12	0.690
AKN	0.60	0.036
VRI	0.66	0.019
CIW/ACN	0.68	0.015
SA/R	0.30	0.330
CIA	0.80	0.002
PIA	0.79	0.002
STI	0.27	0.390

Table 4. Details of regression statistics for the parameters and indices

Indices	Parameters											
	Compressibility				Strength		In-situ state		Indices			
	λ		N_o		M		v		Ip		Fines	
	r	*p*-value	r	*p*-value	r	*p*-value	r	*p*-value	r	*p*-value	r	*p*-value
Depth	0.58	0.049	0.61	0.026	0.36	0.203	0.72	0.0001	0.52	0.011	0.68	0.007
Fines	0.44	0.118	0.48	0.110	0.78	0.003	0.52	0.067	0.80	0.002	-	-
Clay minerals	0.17	0.660	0.22	0.590	0.67	0.040	0.31	0.379	0.73	0.024	0.67	0.033
Quartz	0.07	0.96	0.09	0.81	0.30	0.42	0.53	0.115	0.69	0.038	0.76	0.011
Ip	0.50	0.094	0.58	0.061	0.76	0.003	0.60	0.041	-	-	-	-
WIP	0.65	0.021	0.78	0.005	0.31	0.331	0.90	0.0001	0.62	0.043	0.68	0.015
WPI	0.75	0.029	0.82	0.021	0.68	0.061	0.90	0.003	0.76	0.049	0.93	0.001
PI	0.84	0.001	0.83	0.001	0.61	0.036	0.63	0.027	0.68	0.020	0.64	0.024
SOC	0.85	0.001	0.84	0.001	0.64	0.025	0.69	0.014	0.74	0.009	0.66	0.019
LOI	0.75	0.022	0.81	0.025	0.74	0.037	0.88	0.003	0.77	0.044	0.90	0.003
Hc	0.82	0.011	0.88	0.009	0.82	0.012	0.86	0.005	0.94	0.002	0.79	0.018
Lc	0.42	0.172	0.57	0.067	0.19	0.544	0.80	0.002	0.49	0.119	0.53	0.075
Rc	0.72	0.007	0.77	0.006	0.65	0.022	0.76	0.004	0.78	0.004	0.66	0.018
Kr	0.68	0.015	0.66	0.026	0.65	0.021	0.46	0.132	0.61	0.046	0.48	0.111
AKN	0.69	0.013	0.75	0.008	0.61	0.037	0.79	0.002	0.78	0.004	0.63	0.028
VRI	0.63	0.027	0.63	0.039	0.14	0.669	0.58	0.048	0.49	0.121	0.53	0.074
CIW/ACN	0.55	0.062	0.59	0.056	0.05	0.866	0.57	0.050	0.58	0.061	0.69	0.013
SA/R	0.76	0.004	0.75	0.007	0.60	0.038	0.59	0.043	0.69	0.019	0.56	0.057
CIA	0.68	0.015	0.79	0.003	0.34	0.277	0.88	0.0002	0.68	0.021	0.73	0.007
PIA	0.66	0.019	0.74	0.009	0.20	0.529	0.81	0.001	0.55	0.081	0.74	0.006
STI	0.81	0.002	0.79	0.003	0.62	0.032	0.60	0.004	0.67	0.023	0.53	0.072

Table 5. Correlations between the indices and compressibility parameters

Correlations	r	*p*-value
$\lambda = 0.0040(SOC)+0.000012$	0.85	0.001
$N_o = 0.0395(SOC)+1.309$	0.84	0.001
$\lambda = -0.0040(PI)+0.356$	0.84	0.001
$N_o = -0.0364(PI)+4.922$	0.83	0.001
$\lambda = 0.0040(LOI)+0.290$	0.75	0.022
$N_o = 0.0505(LOI)+1.531$	0.81	0.025
$\lambda = -0.0030(WPI)+0.087$	0.75	0.029
$N_o = -0.0345(WPI)+2.174$	0.82	0.021
$\lambda = -0.0060(STI)+0.544$	0.81	0.002
$N_o = -0.0588(STI)+6.809$	0.79	0.003
$\lambda = -0.0390(SA)+0.256$	0.76	0.004
$N_o = -0.0397(SA)+3.912$	0.75	0.008
$\lambda = 0.0077(Hc)+0.081$	0.82	0.011
$N_o = 0.0867(Hc)+2.095$	0.88	0.009

Table 6. Correlations between the indices and strength parameter

Correlations	r	*p*-value
$M = -0.0135(Hc)+1.488$	0.82	0.012
$M = -0.0071(F)+1.867$	0.78	0.003
$M = -0.0090(Ip)+1.618$	0.76	0.012
$M = -0.0076(LOI)+1.571$	0.74	0.037
$M = -0.0060(Cm)+1.637$	0.67	0.040
$M = 0.0046(WPI)+1.474$	0.68	0.061
$M = -0.0051(SOC)+1.611$	0.64	0.025

Table 7. Correlations between the indices and in-situ specific volume

Correlations	r	*p*-value
v = -0.0071*(WIP)*+2.210	0.90	0.00001
v = -0.0170*(WPI)*+i.647	0.90	0.003
v = 0.0137*(CIA)*+0.876	0.88	0.0002
v = 0.0250*(LOI)*+1.332	0.88	0.003
v = 0.0390*(Hc)*+1.632	0.86	0.006
v = 0.0126*(PIA)*+0.835	0.81	0.001
v = 0.0310*(Lc)*+1.530	0.80	0.002
v = 0.0500*(AKN)*+1.643	0.79	0.002
v = 0.0226*(Rc)*+1.697	0.76	0.004
v = 0.0140*(SOC)*+1.413	0.69	0.014

Table 8. Cross correlations between some indices

Correlations	r	*p*-value
Ip = 1.466*(Hc)*+7.935	0.94	0.002
F = -1.189*(WPI)*+43.619	0.93	0.001
F = 1.755*(LOI)*+21.945	0.90	0.003
Ip = 0.605*(F)*-17.503	0.80	0.002

Table 9. Classification of correlation coefficients (after Evans, 1996)

Correlation coefficient (r) value	Qualitative description of Strength	Tentative numerical value
0.00-0.019	very weak	0
0.20-0.39	weak	5
0.40-0.59	moderate	10
0.60-0.79	strong	15
0.80-1.0	very strong	20

Table 10. Summary of the overall performance of the indices

Indices	Numerical value for performance (%)	Qualitative description of Performance
Depth	56	good
Fines	56	good
Clay minerals	31	weak
Quartz	18	very weak
Ip	63	good
WIP	69	good
WPI	88	best
PI	88	best
SOC	88	best
LOI	88	best
Hc	100	best
Lc	50	good
Rc	75	best
Kr	69	good
AKN	75	best
VRI	56	good
CIW/ACN	38	weak
SA/R	69	good
CIA	69	good
PIA	69	good
STI	81	best

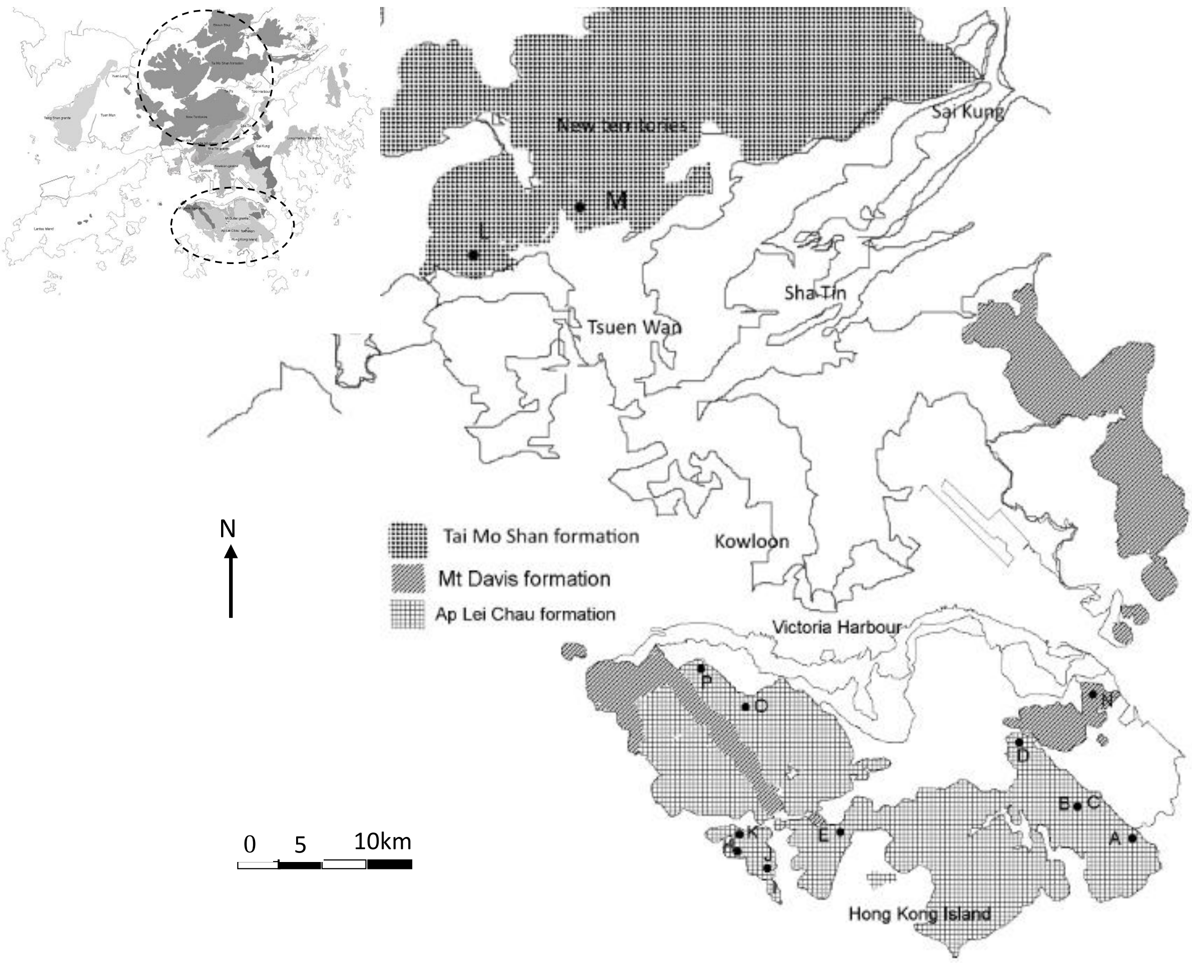

Figure 1: Map of the sample locations

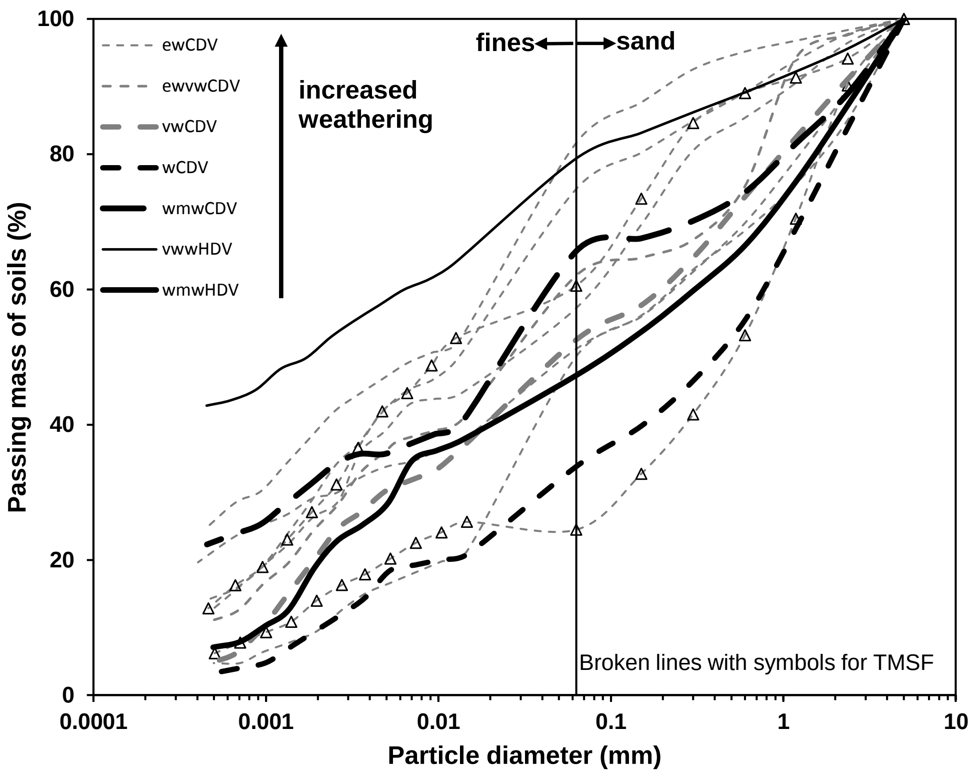

Figure 2: Particle size distribution curves for the samples and estimation of fines content (modified from Okewale & Coop, 2017)

ew extremely weak, ewvw extremely weak to very weak, vw very weak, w weak, wmw weak to medium weak, vww very weak to weak, CDV completely decomposed volcanic rock, HDV highly decomposed volcanic rock

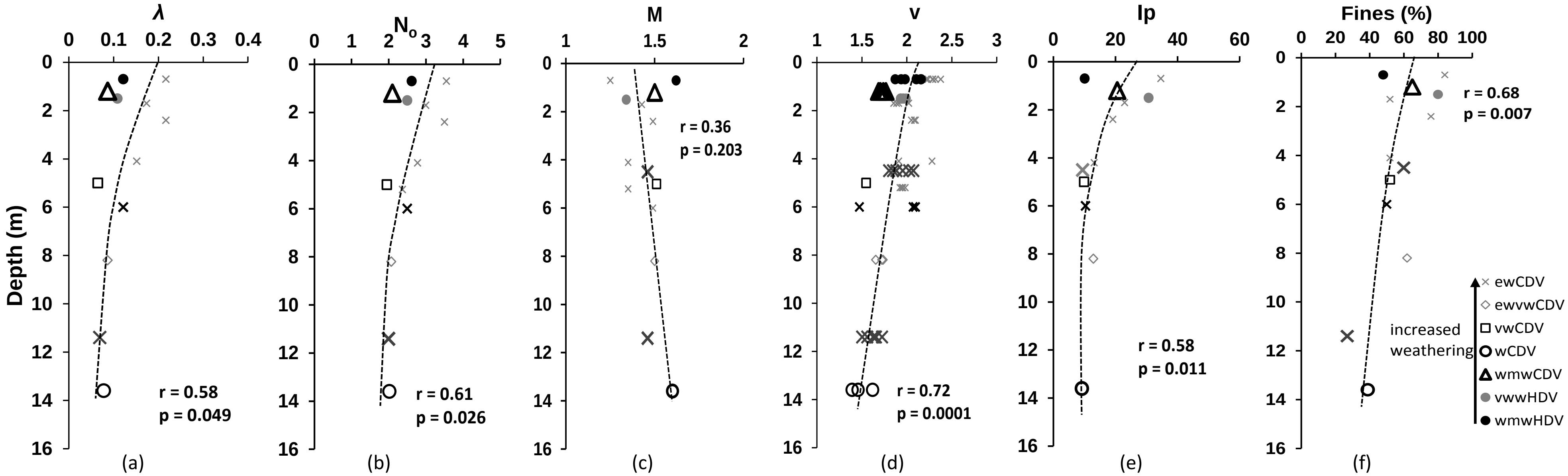

Figure 3: Variation of parameters and indices with depth (adapted from Okewale & Coop, 2017)

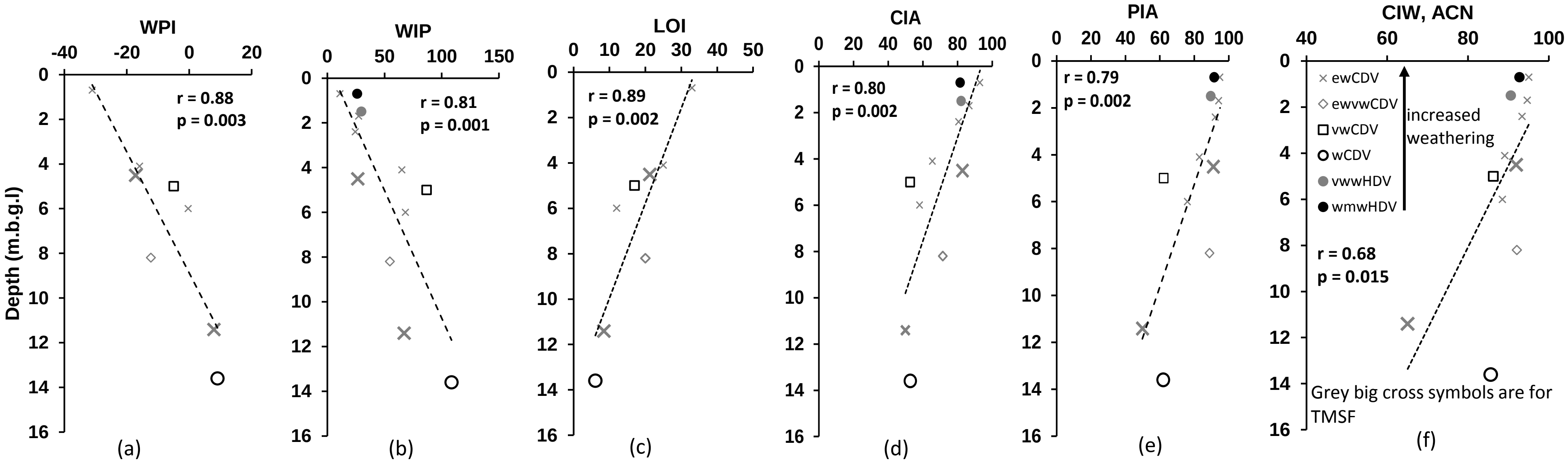

Figure 4: Variation of some selected chemical weathering indices with depth

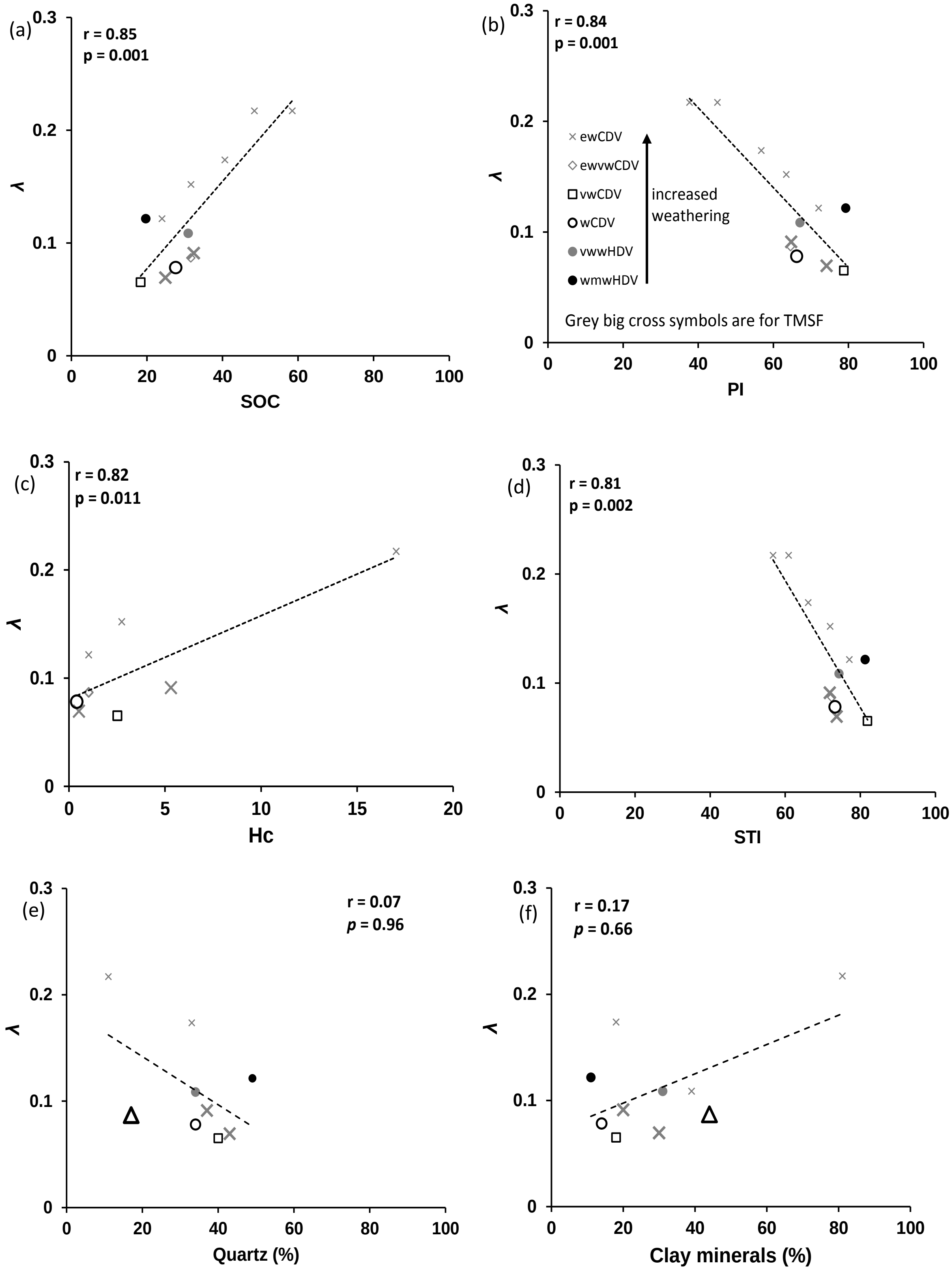

Figure 5: Variation of compressibility parameter λ with indices

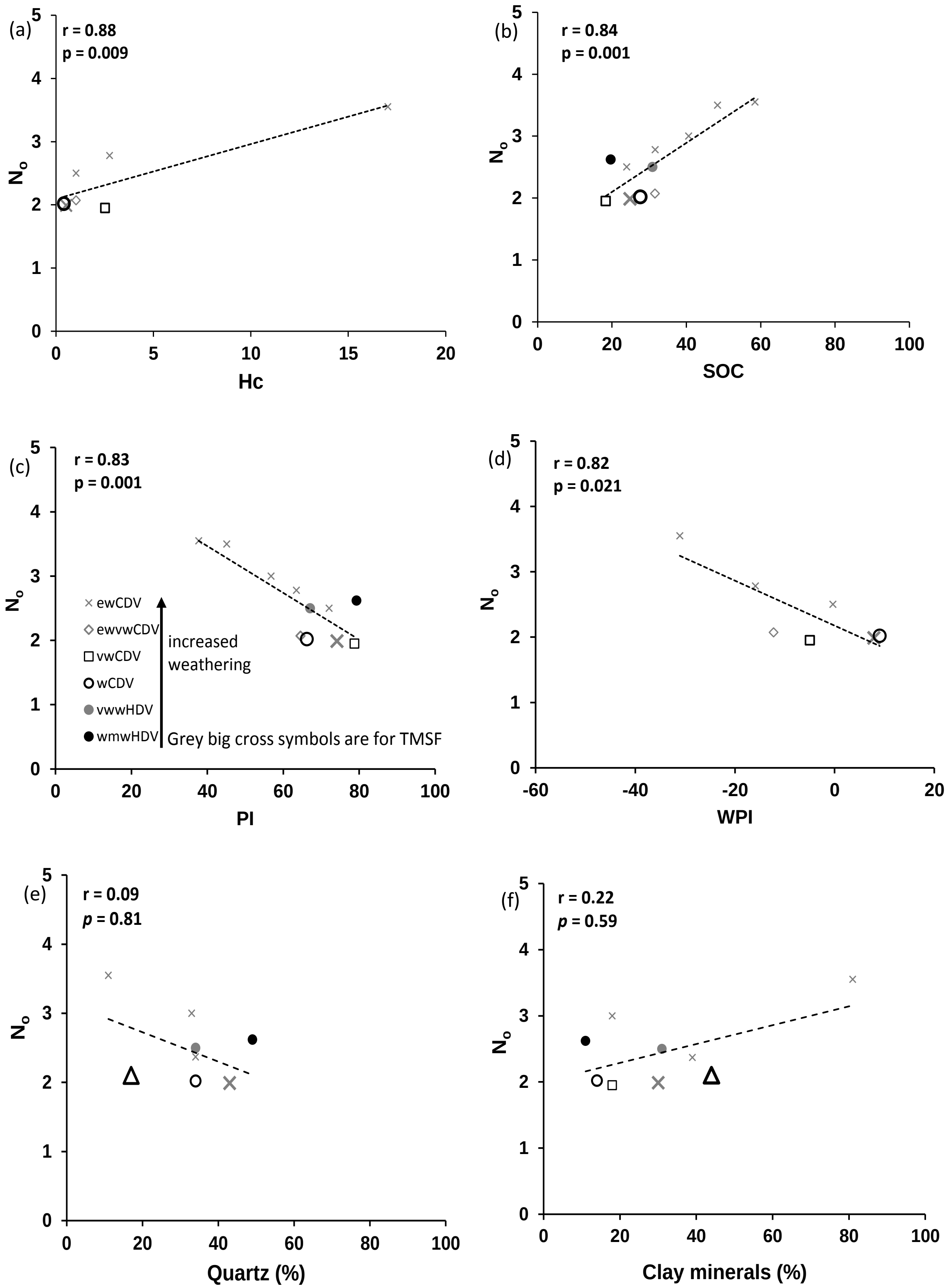

Figure 6: Variation of compressibility parameter N_o with indices

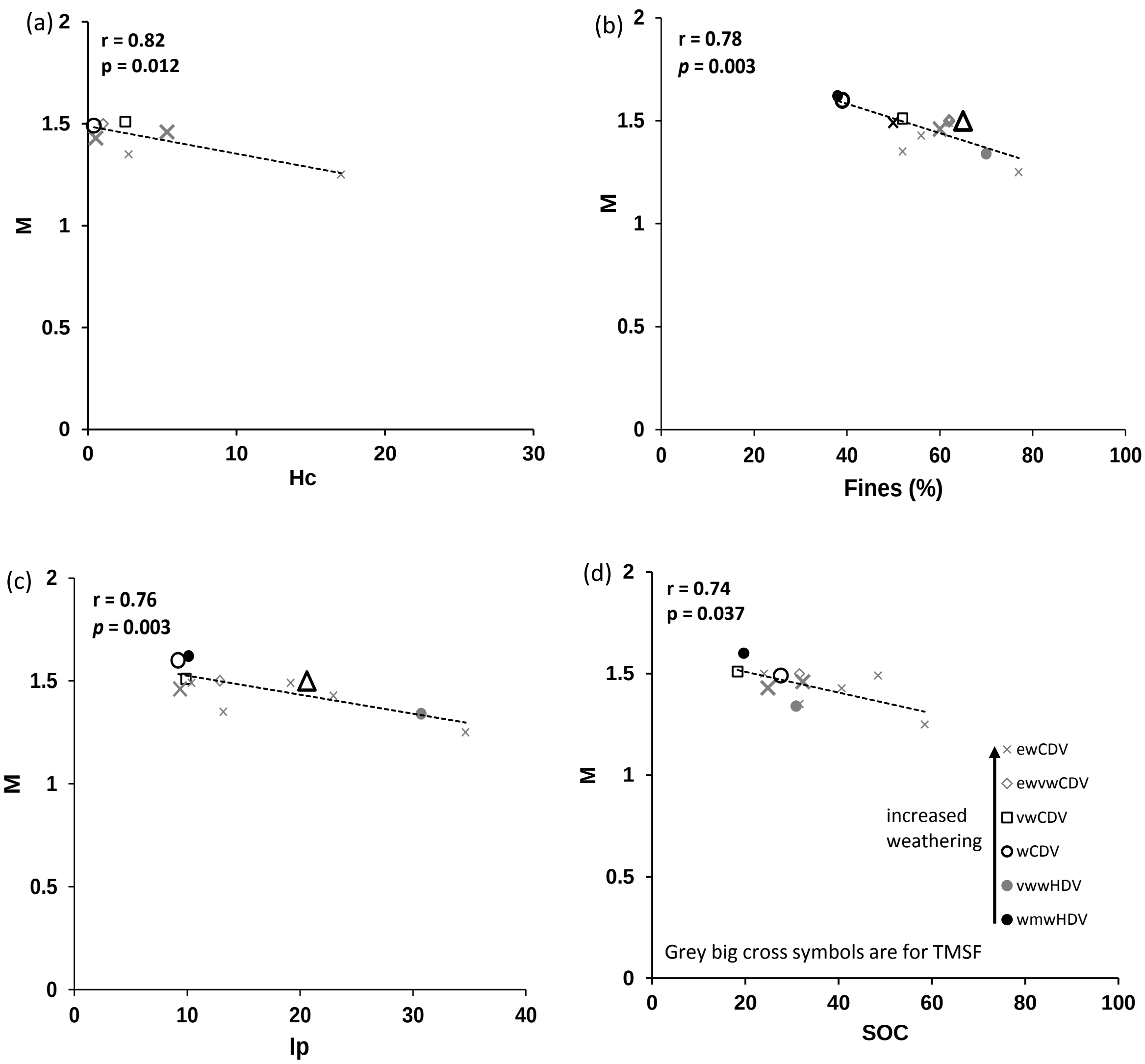

Figure 7: Variation of strength parameter M with indices

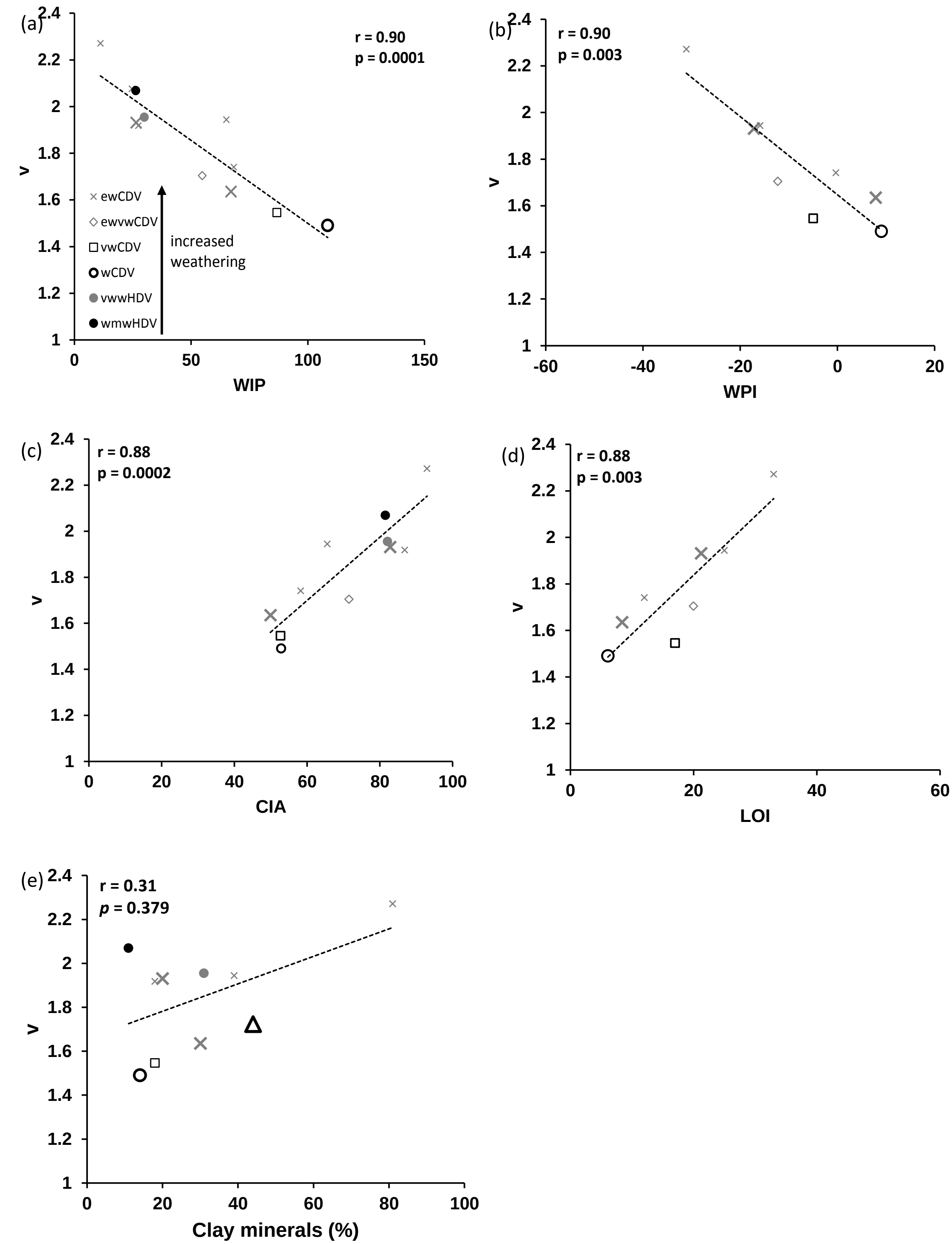

Figure 8: Variation of in-situ v with indices

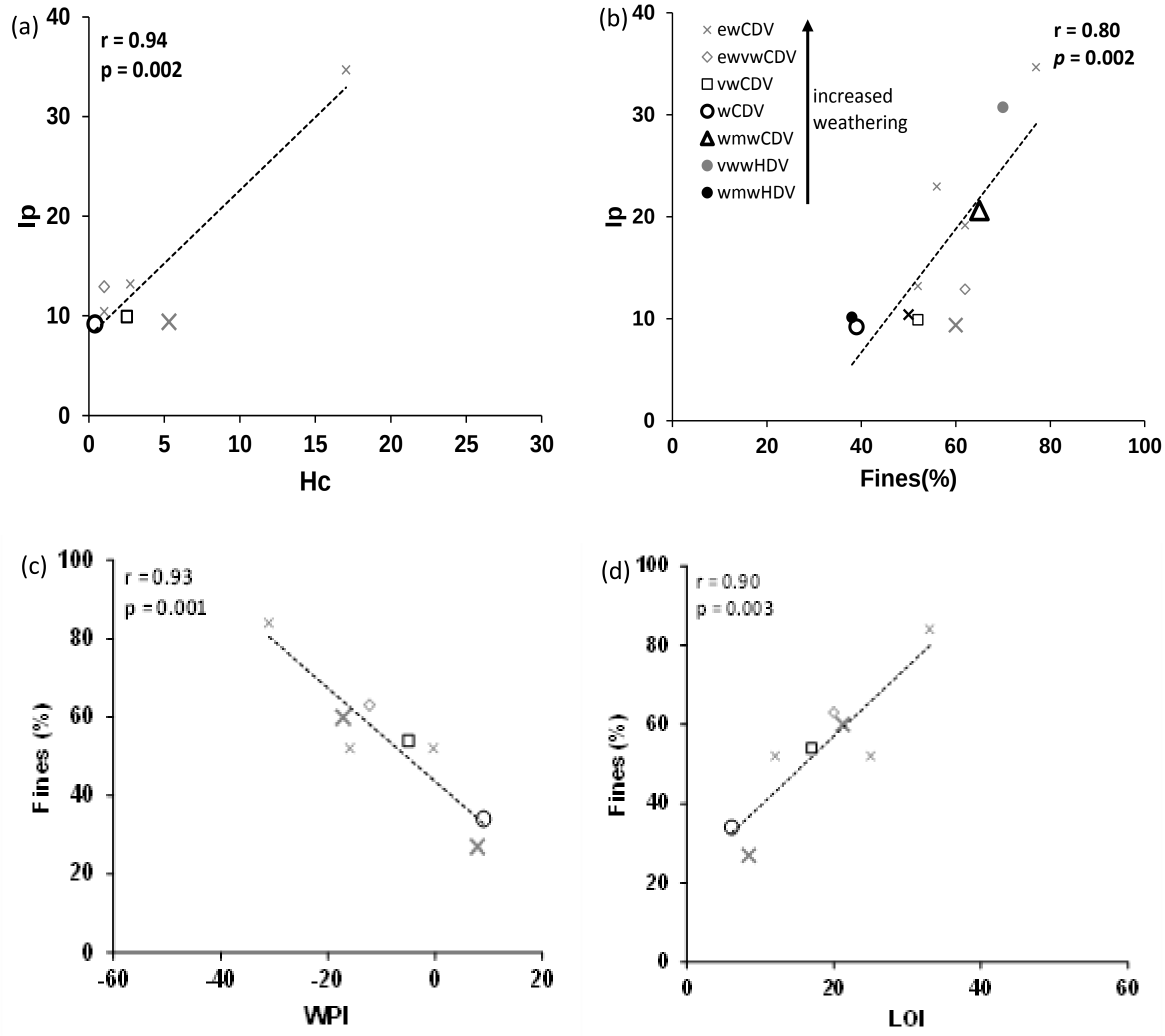

Figure 9: Cross correlations between the indices